The Chinese Magnetic Fusion Program

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On behalf of MCF community of China

Nov. 7-9 2022

MCF research largely guided by National Magnetic Confinement Fusion Science Program （MOST）

- **To support R&D needed for ITER construction （PAs） and Operation**
- **To establish S&T basis required for CFETR design and construction**

In last few years, projects distribute on:

- **Research of Integrated CFETR design**
  - For proposing project, figuring-out R&D needs
- **Fusion Science research in support of ITER and CFETR**
  - Augmenting research capabilities (EAST and HL-2M; facilities in uni.-level)
  - Research on reactor-relevant key physics and technology (TC, MHD, EP, Dia, Contrl…)
  - Research on development of ITER/CFETR relevant operation scenarios.
  - Extending collaboration based on EAST/HL-2M (international, domestic , ITPA)
- **R&D of Reactor key technology and components** （in addition to ITER PAs）
  - Advanced superconducting magnets and vacuum vessel
  - Heating and current drive technologies
  - Fusion reactor material in component scale
  - Tritium self-sufficient technology and Remote handling
- **University Research and Young Scientist program**

Physics Projects in National Magnetic Confinement Fusion Science Program support Fusion Community diversely

- **EAST on integrated advanced steady-state scenarios**
  - SSO scenarios (high f_{bs}, β_p, f_{GW}； ELM and impurity control, core-edge integration…)
  - ITER Pre-Nuclear phase scenarios (H/He plasma and full-metal wall)
  - Collaboration (ITPA:Div/SOL、PEP, international and domestic: high β_p、H/He plasma）
- **HL-2A/2M on high performance scenarios**
  - High performance operation scenarios (high β_N, I_p； Div/SOL and MHD control, EP…)
  - Collaboration (ITPA:MHD、TC, international and domestic: Edge、AI Control)

Mission-driven

EAST&HL-2A/M joint actions

User facilities

- **University and Non-tokamak researches**
  - University scale facilities: JTEXT, FRC, Stellerator, ST, linear-device for PMI…
  - Theory/modeling/simulation and diagnostics (EP, MHD, TC,…)
- **Young Scientist program** (majorly oriented to Uni.)
  - Free research (two topics with 5 persons/each/year)
  - Encourage collaboration with major facilities

Free-research

Mission-driven

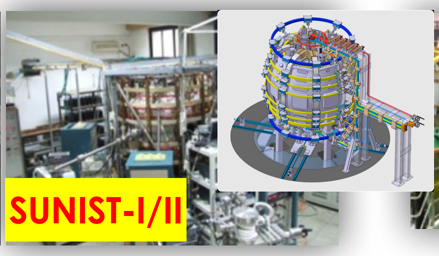
Supporting team

Education/Training

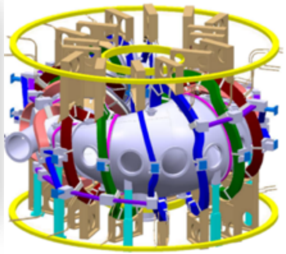
Major fusion device in China

Congratulation to 1000s!

Congratulation to 1MA!

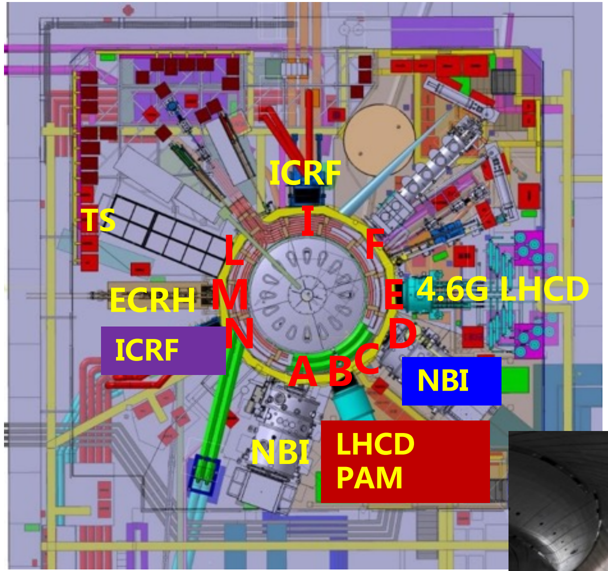


CFQS主机

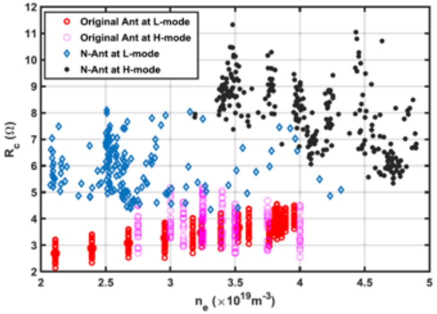


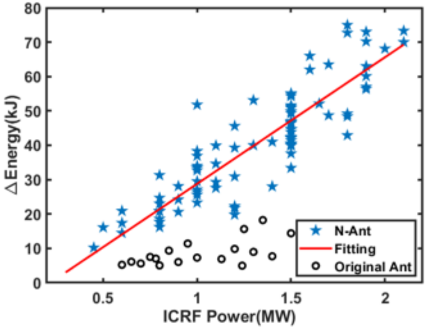
Major Progress on EAST and HL-2A/M Experiments

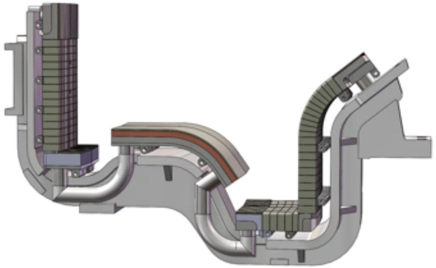
Recent EAST Upgrade allow higher H&CD power & capable of exploring scenarios with full metal wall

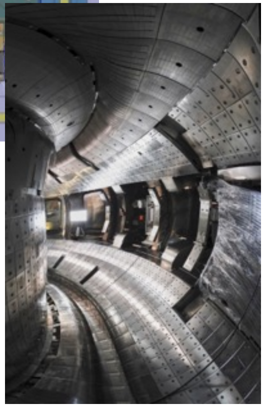


- New ICRF antenna with smaller $k_{||}$ improves coupling and heating efficiency









- One more gyrotron (1MW@140GHz)
- New lower W-divertor: closed outer- and open inner divertors for balanced detachment
- Since 2020 full metal PFC

Efforts on Key issues in supporting long pulse H-mode operation on EAST

High performance

Core

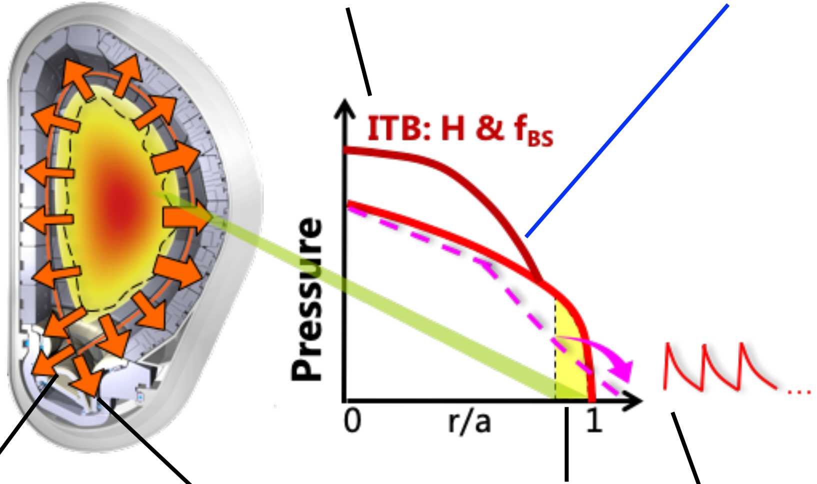
Integration

Edge

H-mode edge sustainment

Impurity Accumulation

Non-inductive j(r) @ >τ_{CR}
Confinement & stability



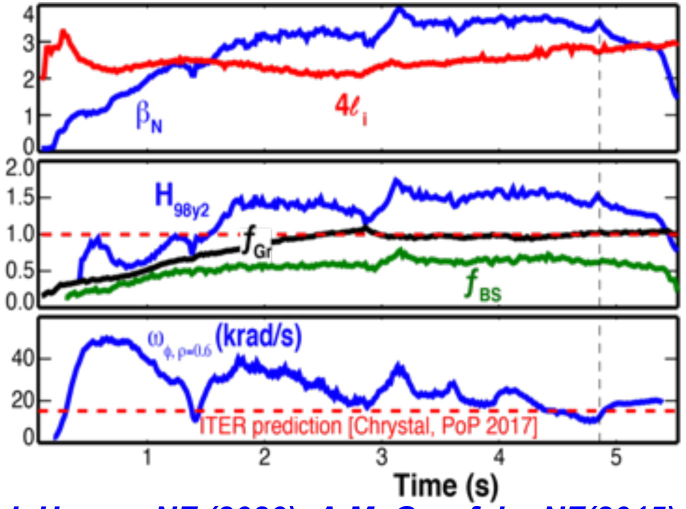
Particle Recycling @ τ_{Wall}

Heat flux at divertor

ELM mitigation
No/small ELM

Joint DIII-D/EAST research on high β_P H-mode scenario
Broad current profile delivers high stability & confinement

ε^{-1}~2.6



J. Huang, NF (2020) ,A.M. Garofalo, NF(2015)

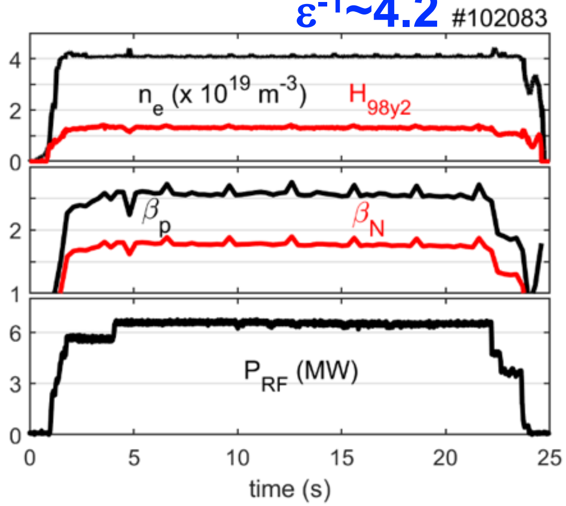
$f_{BS} \sim \beta_P \sqrt{\varepsilon}$

High β_N

Long pulse

High H_{98y2}, n_e, & f_{BS}
Low rotation

ε^{-1}~4.2



X. Gong, NF (2019)

DIII-D fully non-inductive

- Balanced beam, low torque
- H_{98y2}~1.5, β_P≥3, β_N≥4*l_i, f_{bs}~0.8

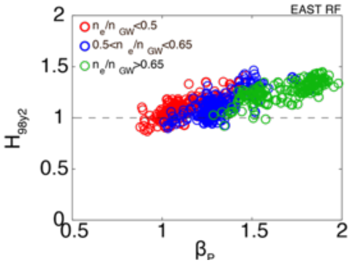
EAST fully non-inductive, **long pulse**

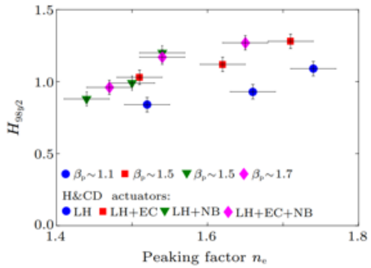
- RF: H_{98y2}~1.3, β_p~2.5, β_N~1.8 , f_{bs}~0.5
- RF + NB: H_{98y2}~1.2, β_p~3.1, β_N~2.1

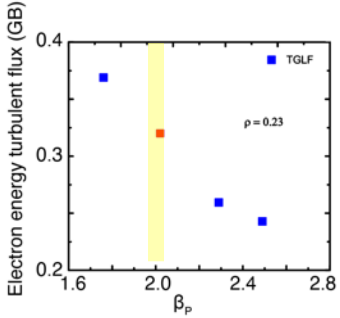
The physics mechanism behind the improved energy confinement in long-pulse high β_P H-mode on EAST

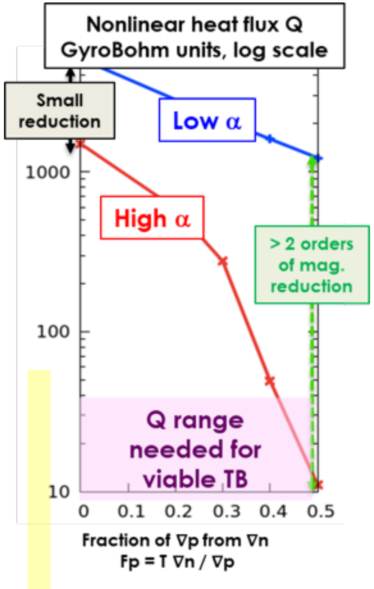
- **Improved H_{98y2} at higher β_P**
  - TGLF: turbulent Q_e decreases with the increase of β_P
  - High β_P facilitates weak negative shear, and promote ITB formation
- **H_{98y2} depends on ∇n_e in various Heating/CD mixtures**
  - TGLF: enhanced Shafranov shift stabilizing effect on turbulent transport by high ∇n_e in high β_P regime
  - Instability cannot feed ∇n_e due to poor coupling to trapped electrons

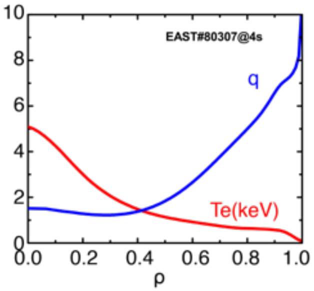
J.P. Qian, PoP (2021)
B.N. Wan, CPL (2020)





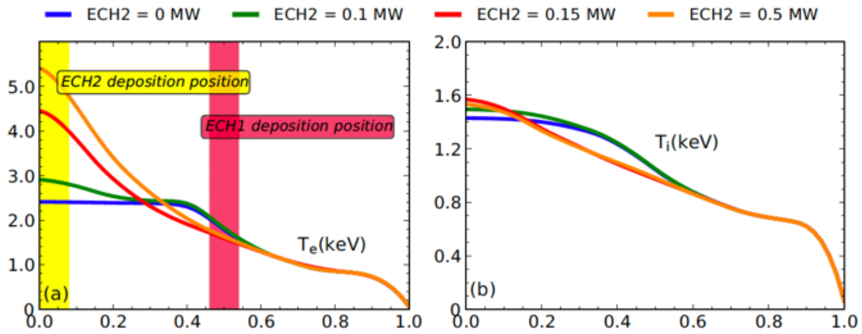


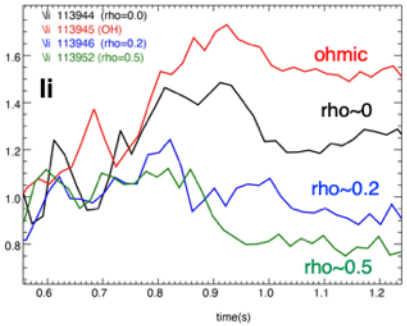


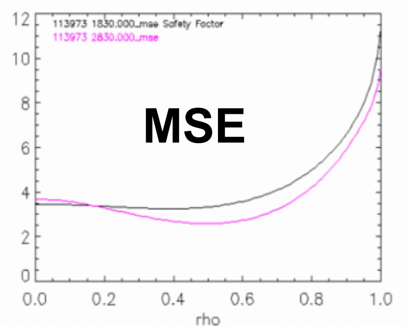


Modeling and experiment show that current profile becomes broader with off-axis EC

- ITB inside ρ<0.4, could we expand?
- Centrally deposited ECH increases j(r) and Te on the axis
- Early heating of off-axis EC resulted in reversed shear with lower li
  - Challenge for low current ramping-rate and high aspect ratio
  - q_{min}>2.0 observed with MSE constraint
- Exploring for higher β_P & f_{BS} with ITB at larger radius, but challenge for steady-state

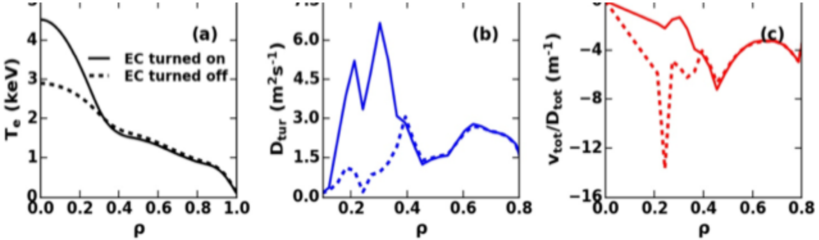


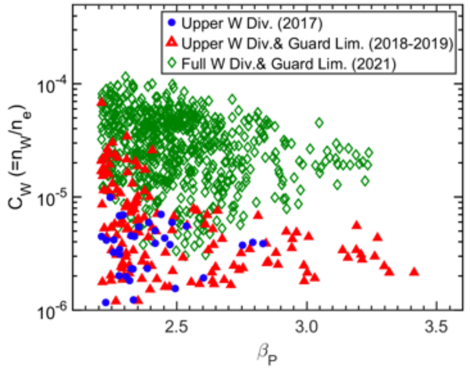


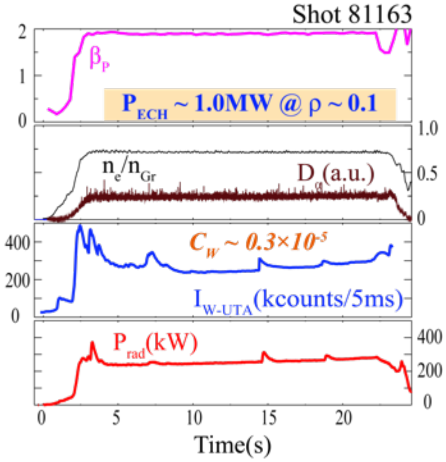


Low C_W is maintained with full tungsten divertor operation

- ~ 4 times increase of C_W with full tungsten divertor
- Small ELMs and high density reduced W-sputtering
- W accumulation in the improved core confinement regime due to large **neoclassical inward convection**
- Tungsten accumulation avoided by on-axis ECH (QuaLiKiz and NEO Modeling)
  - Increased turbulent diffusion of TEM inside ρ<0.45
  - Reduced the ratio V_{pin}/D_{tot}





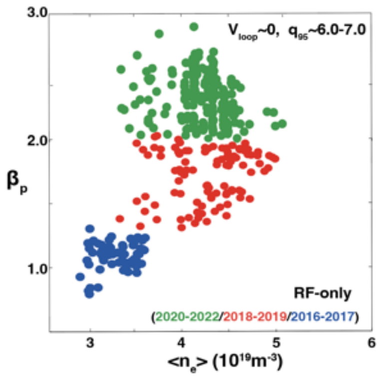


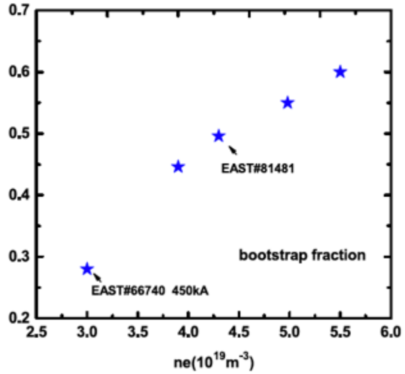
- Similar effect also observed by on-axis ICRH

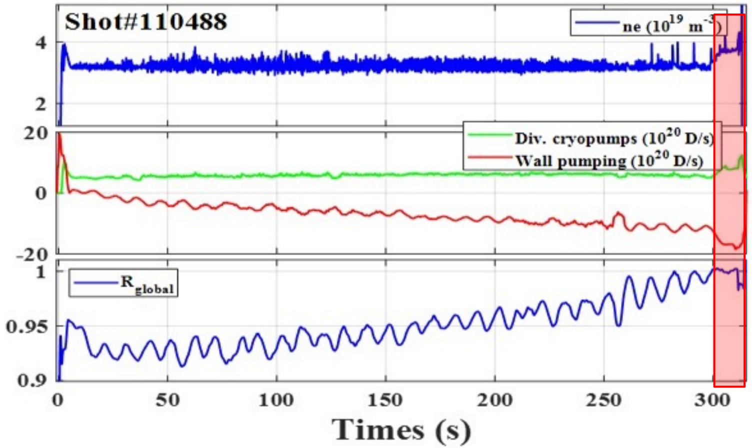
L. Zhang 2nd CFEC 2021 S.Y. Shi NF(2022)

The regime of high β_P scenario applied for long pulse H-mode operation under ITER-like conditions

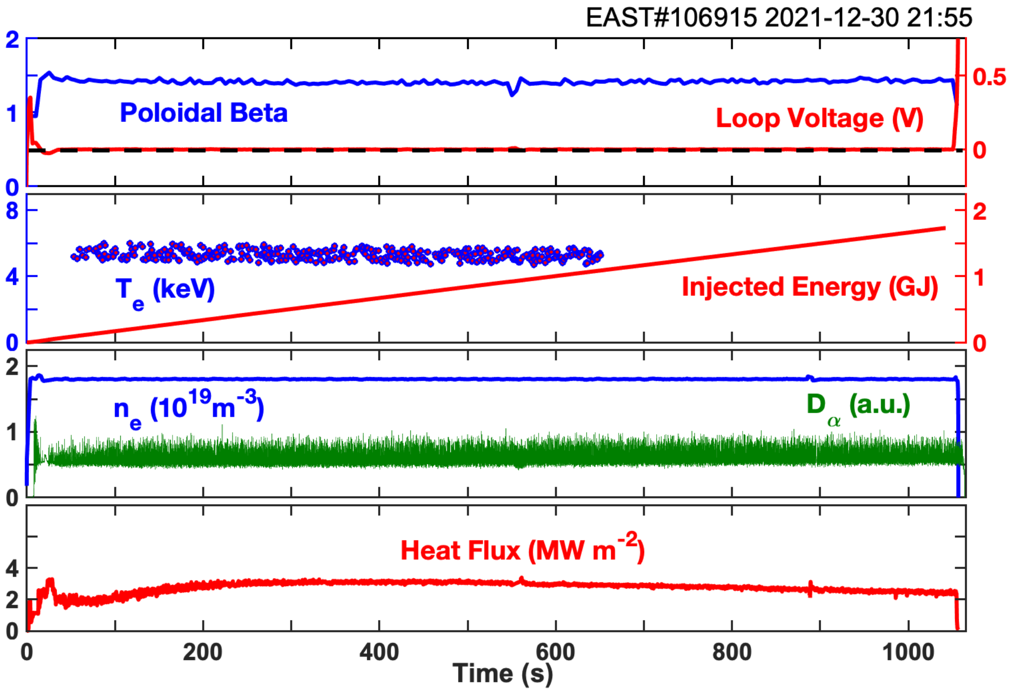
- Fully non-inductive with q_{95}~6.0-7.0
- Extended operational space with improved conf.
  - High f_{GW}~0.8, β_p ~ 3, $\beta_N \geq 2$, $f_{bs} \gtrsim 50\%$
  - H_{98y2}~1.4 with e-ITB inside $\rho<0.4$
- ELM and tungsten impurity control
- ITER-like full W-divertor & e-heating dominant and low torque injection
- 300s H-mode with optimized recycling control, but eventually terminated by recycling
  - RF-only: P_{LHW}~2MW, P_{EC}~1.6MW, P_{IC}~1.2MW
  - H_{98y2} >1.3, f_{Gr}~0.6, β_P~2.5, β_N ~1.6, f_{BS}>50%
  - Small ELM (f_{ELM} >2.5kHz)



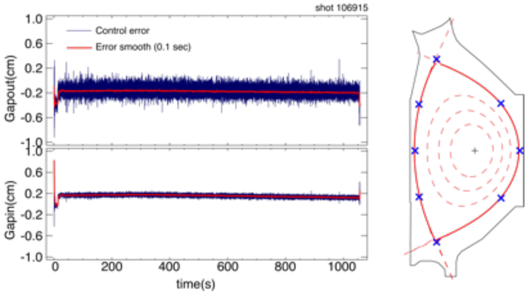




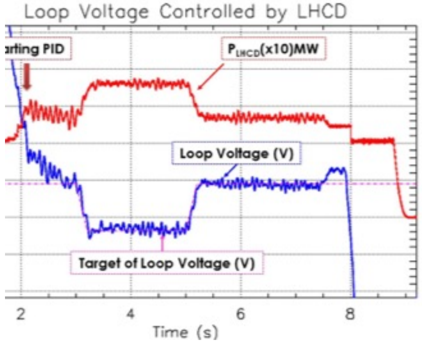
1056s long pulse plasma achieved with roust plasma control under full metal wall



1.7GJ energy injected and exhausted



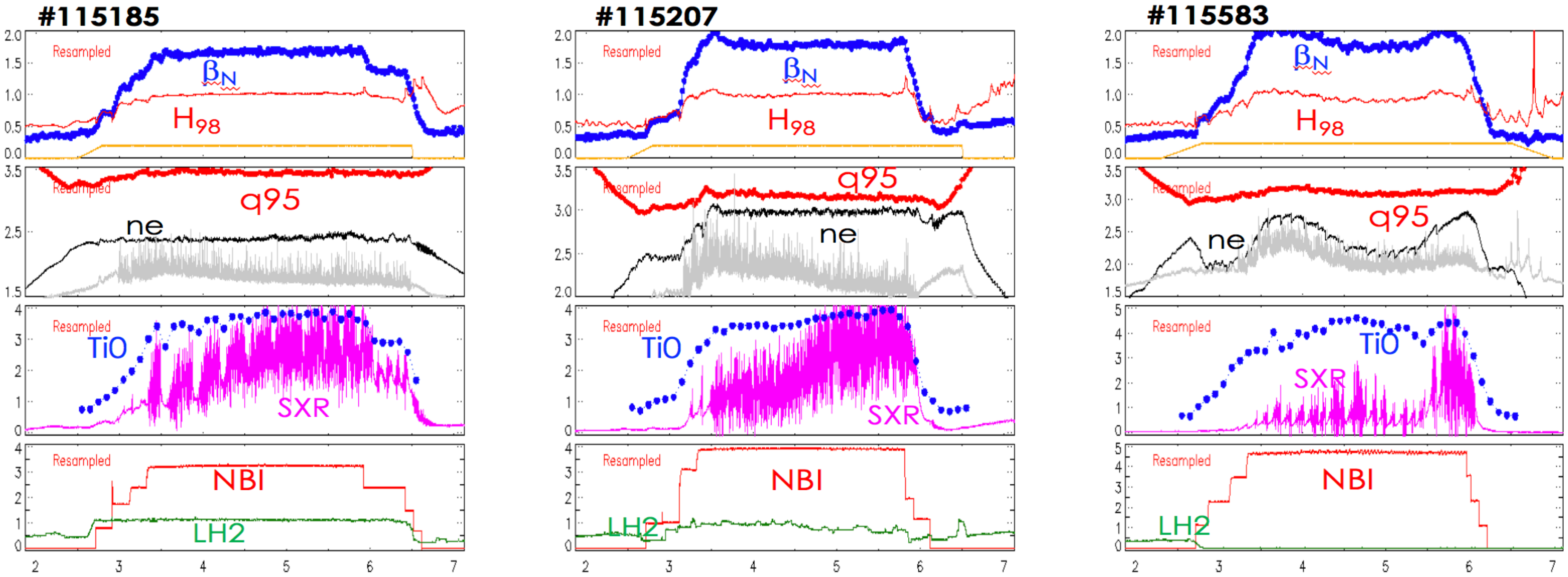
Shape control with new fiber optic current sensors, low drift integrator
Gap <2mm, X-point(R,Z) <3/5mm



Vloop control for fully non-inductive CD

Develop high performance inductive scenario towards ITER baseline-like scenario

- Stationary inductive scenario at q_{95}~3 (B_T~1.5T) with β_N>1.8 and H_{98}≥1.0
- Higher T_{i0} correlates with formation of ITB accompanied with fishbone activities
- A new 1MW gyrotron at 105GHz nearly ready for W pumping-out



ITB Formation correlated with Fast-ion Redistribution

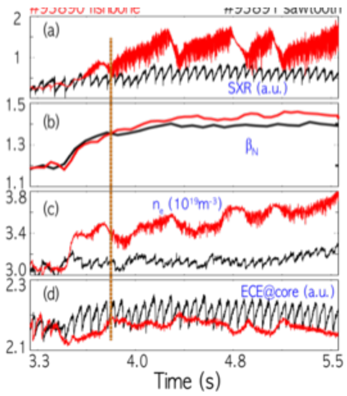
At lower B_T~1.5T, q_{95}~3.5

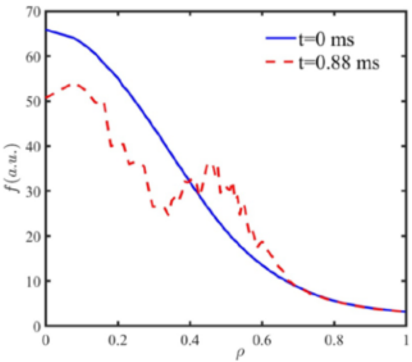
- Fishbone triggered at configuration with resonant q=1;
- ITBs formed simultaneously with fishbone activities;
- M3D-K suggests the role of fast-ion redistribution.

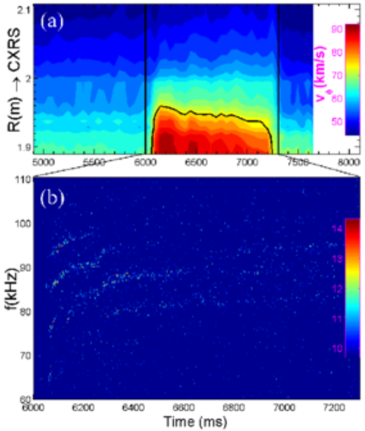
At higher B_T~ 2.2T, q_{95}~6

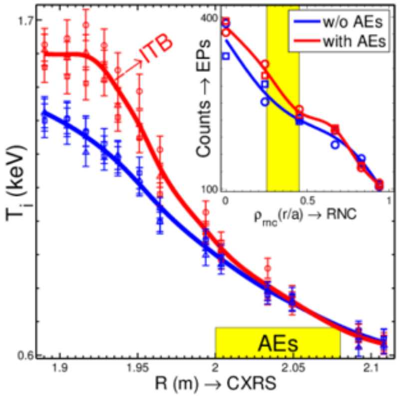
- ITBs formation accompanied with AE excitation;
- Radial neutron camera (RNC) shows redistribution of fast ions.

Z. Liu, **NF** 2020

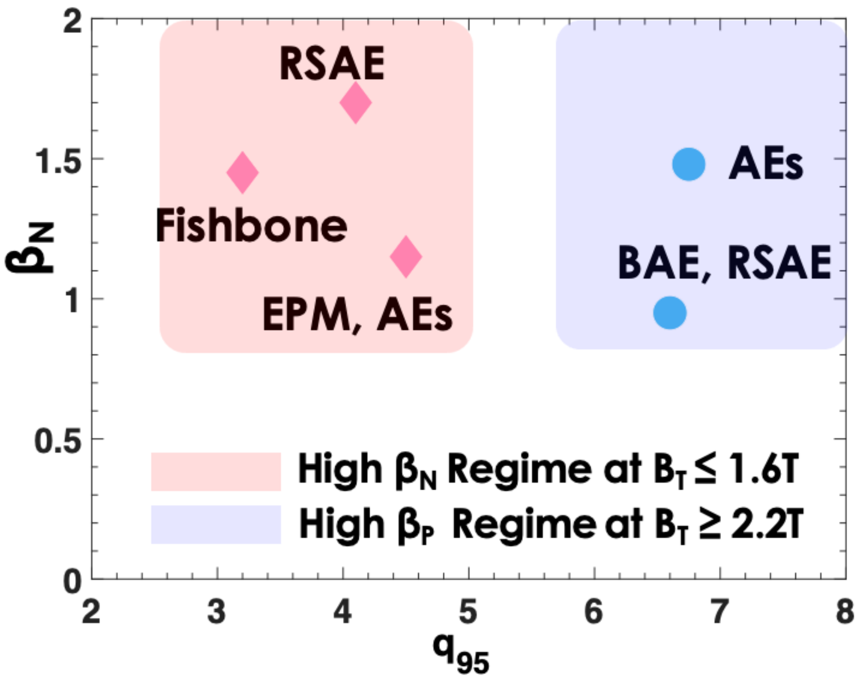




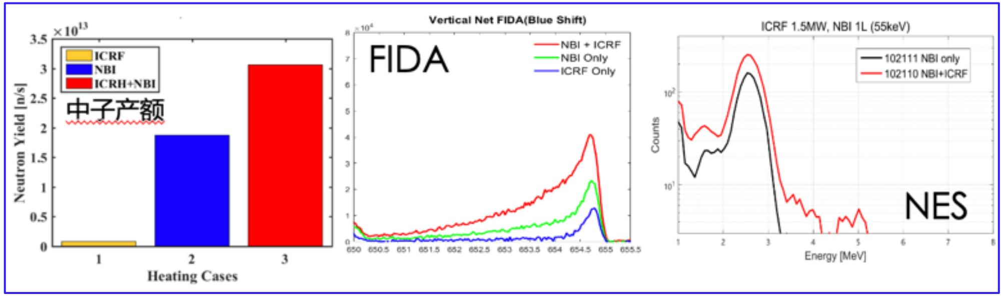




EP related instabilities in high beta regime on EAST

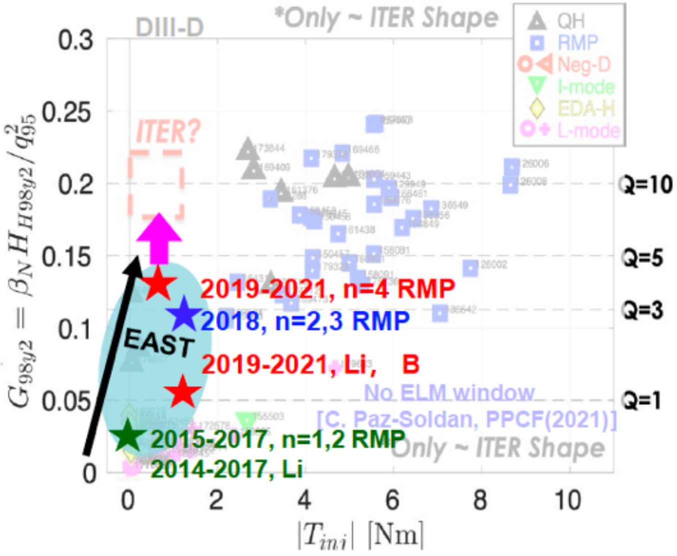


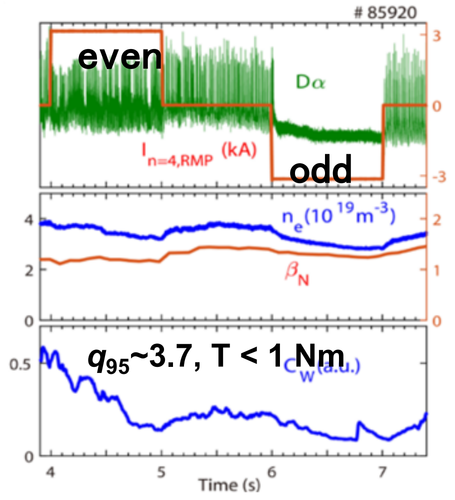
- EP instabilities easier excited: Lower B_T&n_e, Reverse shear, q~1
- Recently enhanced ICRF (~4MW) and NBI capabilities create more EPs and accelerate EPs to MeV

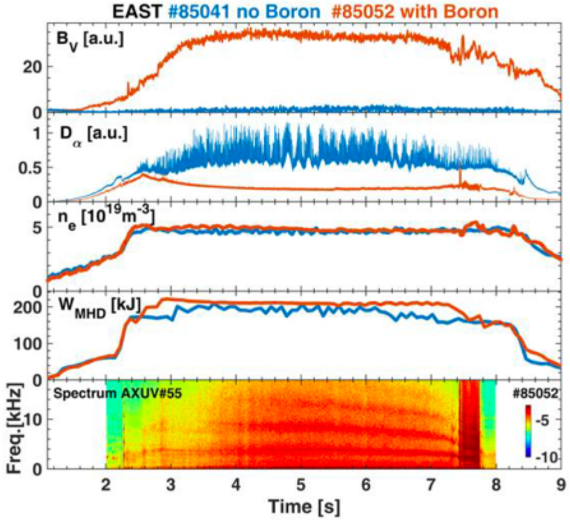


Full ELM suppression in low input torque plasmas in support of ITER

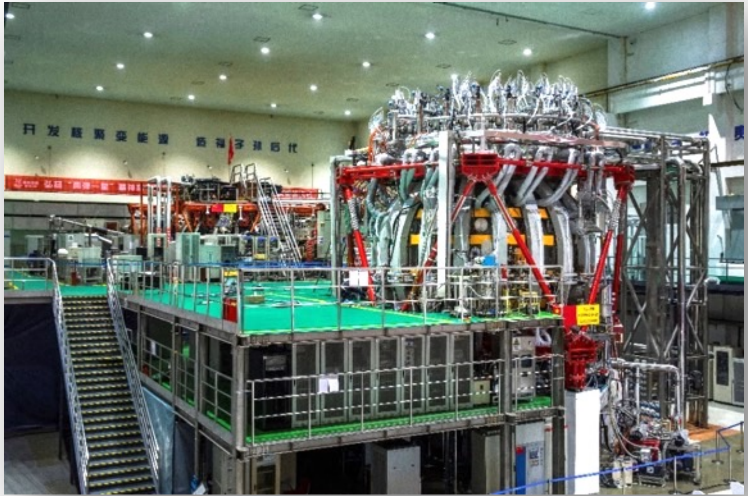
- **ELM suppression by n=4 RMP with small cost of energy confinement**
- **ELMs fully suppressed by Boron power injection with slightly improved confinement**







Features of HL-2M/A allow to access advanced tokamak regimes with flexible divertor configuration



- *R:* 1.65 m
- *a:* 0.40 m
- B_t: 1.2~2.7 T
- I_p: 150 ~ 480 kA
- n_e: 1.0 ~ 6.0 x 10^{19} m^{-3}
- T_e: 1.5 ~ 5.0 keV
- T_i: 0.5 ~ 3.5 keV
- β_N: >3

Heating systems:

- co-NBI (tangential): 3 MW/48keV/1s
- ECRH/ECCD: 68G/140G,5 MW, 500Hz modulation
- LHCD: 3.7G/2 MW

I_p = 2.5 (3) MA

R/a = 2.8（1.78/0.65）

κ = 1.8-2； δ > 0.5

B_T = 2.2 (3) T

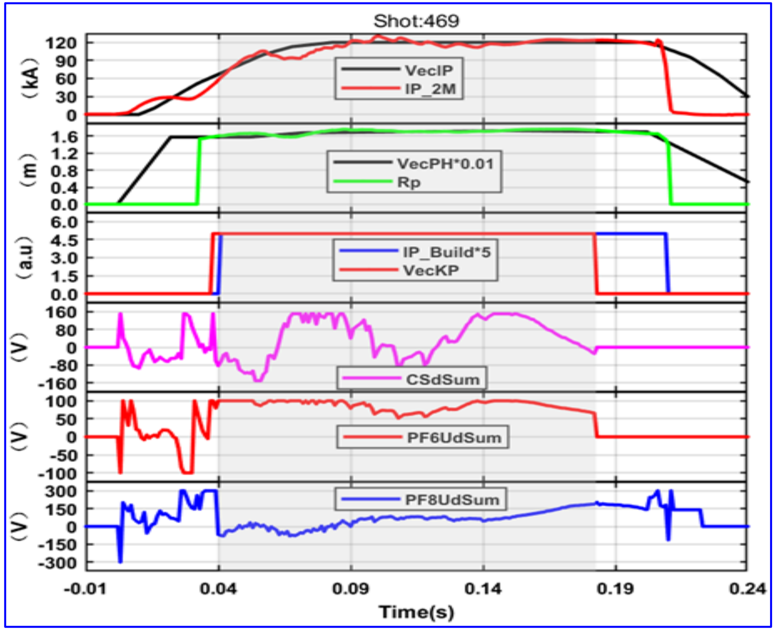
H&CD: 25 (27) MW

(NBI 15+EC 8+LH 2(4))

- AT: high f_{BS}, β, …
- Divertor: snowflake, super-X, ...
- Integrated core-edge solution
- MHD instabilities and disruption
- EP physics,
- …

HL-2M achieved first plasma on Dec. 4th, 2020

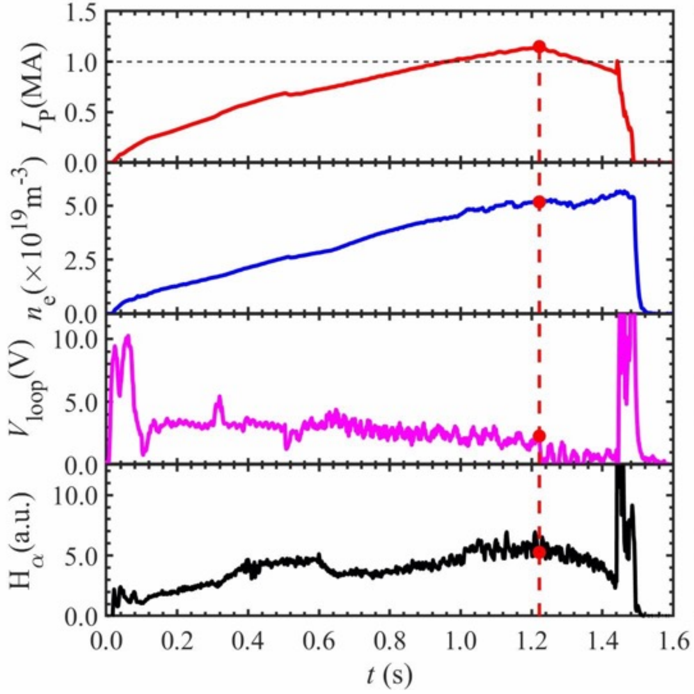
First plasma: >100 kA, >100 ms

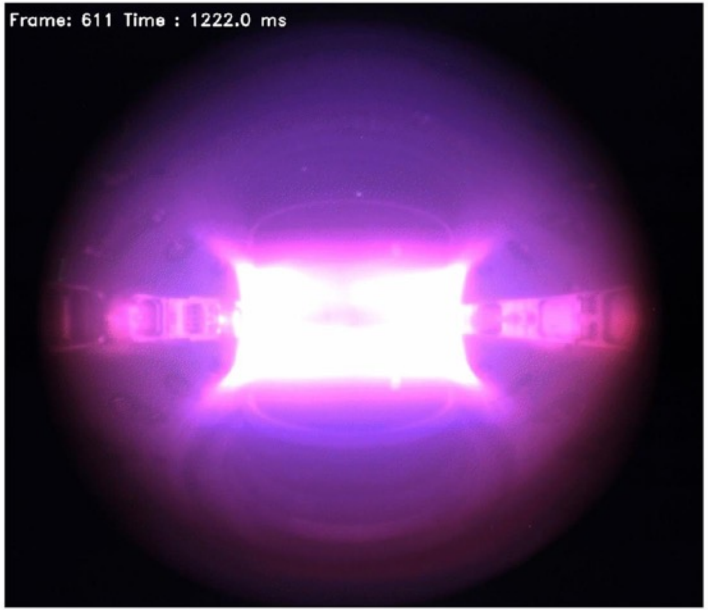


Reported by CCTV News on Dec. 4th, 2020

"Top 10 News of Scientific and Technological Progress in China in 2020"

HL-2M has operated with I_p>1 MA, n_e>5x10^{19} m^{-3} on Oct. 19th, 2022

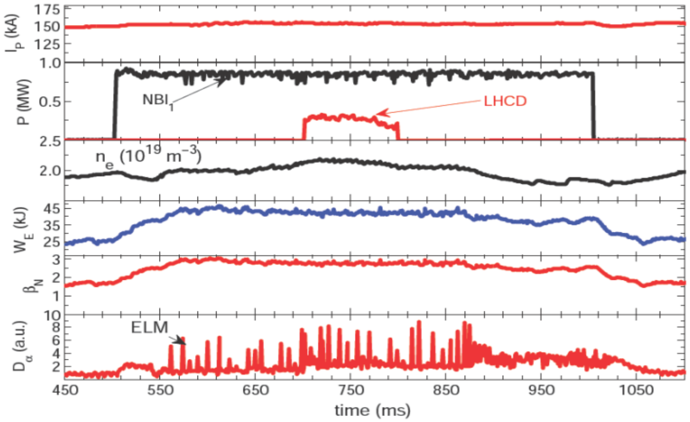




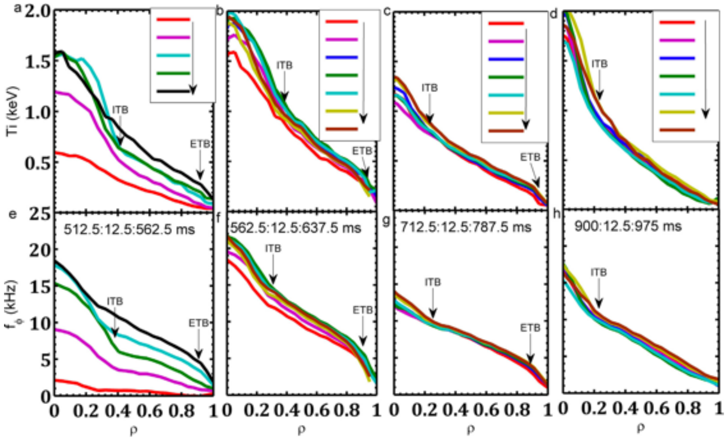
- Inner-Wall Limited Configuration
- $I_{p,max}$ = 1.15MA
- R=1.8m
- a=0.69m
- κ = 1.25
- δ = 0.14

High β_N regimes based on double transport barriers on HL-2A

- **High β_N regime accessed by NBI at low Bt ~1.3T**
  - Sustained β_N >2, for t~15τ_E
  - Transient: β_N >3 @ f_G~0.6, H_{98} ~1.5, q_{95}~4.0
- Hybrid scenario with H-mode edge
  - ITB with high f_ϕ and central weak shear
  - the highest β_N achieved at strong DTBs
- Interesting studies in High β_N H-mode plasmas:
  - MHD instabilities and Alfvénic modes (TAEs and BAEs/EPMs, etc)
  - ITB dynamics by internal kink mode and impurity injection
  - Non-linear mode- coupling



Minor radius ITB + Strong ETB

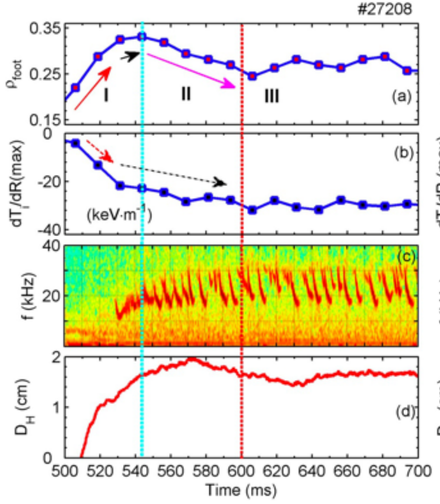


W. Chen, et al., *Fundamental Research* , 2 667 (2022)

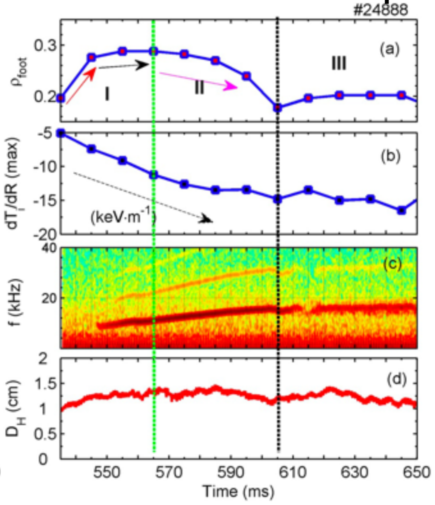
ITB dynamics controlled by internal kink mode

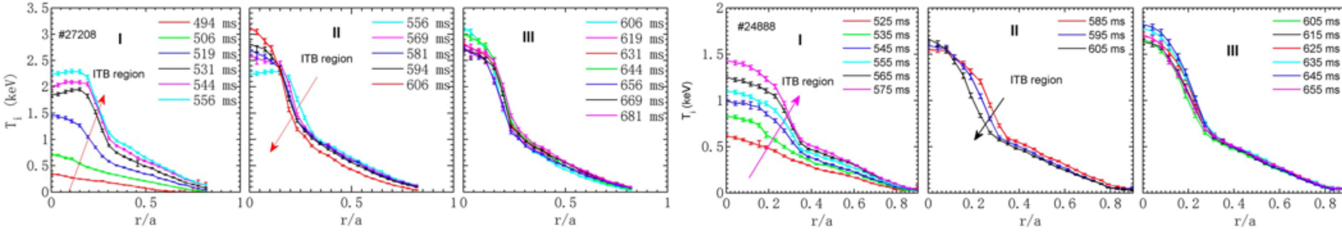
- **ITB formed before IKM**
- **ITB evolved in three phases**
  - I: ITB build-up with increasing radial positon and strength
  - II: shrinks inward as appearance of IKM
  - III: stationary with saturated IKM
- **IKM clamps the ITB foot @ *q*~1** (HB, magnetic flux pumping?)
- **ITBs at larger radius can exist in quiet core plasma, but not be stationary**

FB ITBs @ lower n_e and higher P_{NB}



LLM ITBs @ higher n_e and I_p

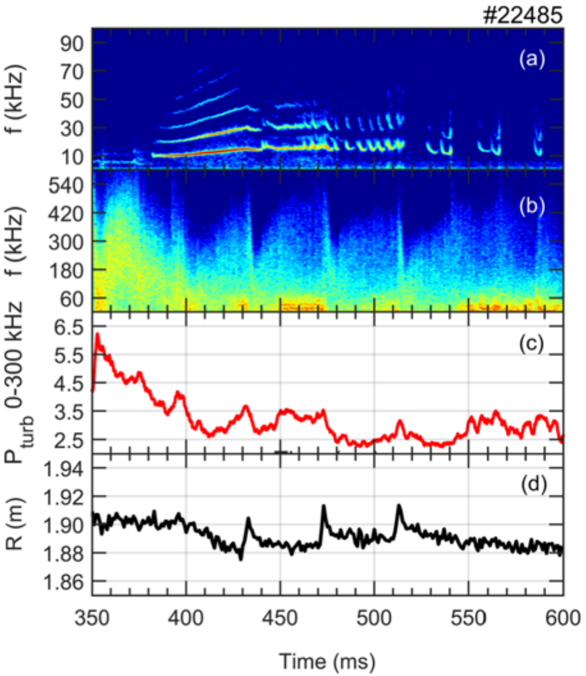


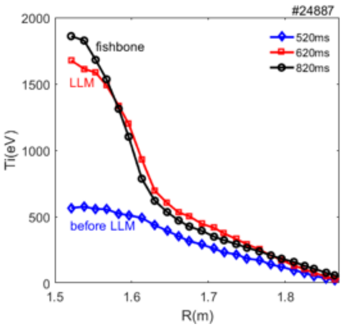


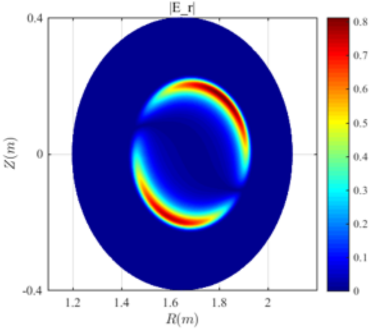
X.X. He, PPCF 64: 015007 (2022)

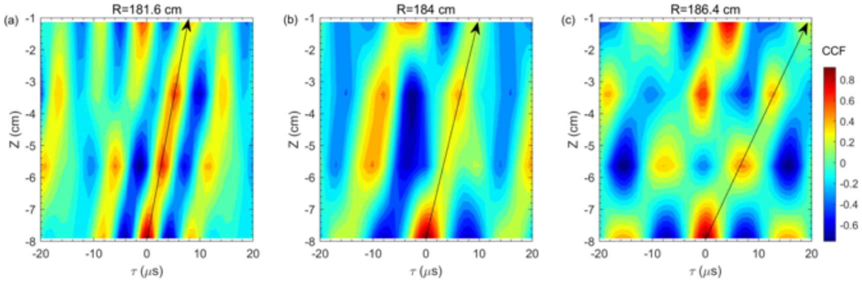
Role of fishbone activity in the formation of ITB

- **Experimental evidences suggest that the fishbone activities can induce a polodial flow, which is beneficial for the suppression of turbulence in the plasma core region.**





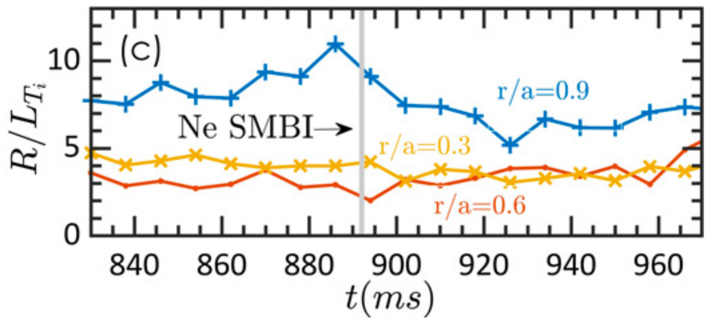




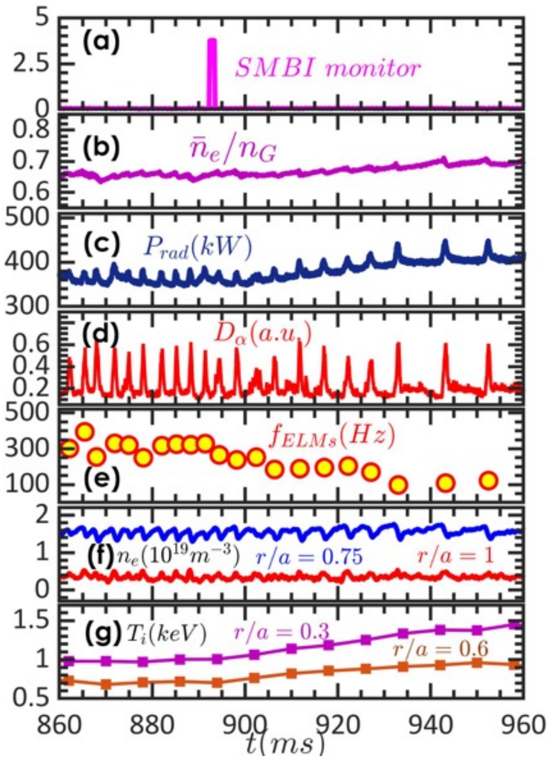
W. Deng, et al., Phys.Plasmas 29 102106 (2022)

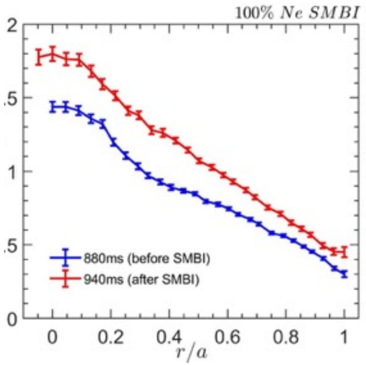
Enhancement of T_i in H-mode by impurity seeding

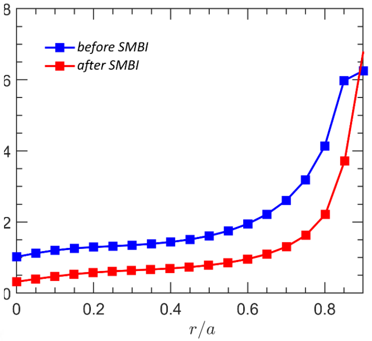
- Reduce the ELM frequency and improve the plasma confinement
- Decreased ITG turbulent transport
- Broader pedestal profile prolonged inter-ELM periods
- Unchanged the core ion stiffness



G.Q.Xue et al., Nucl. Fusion 61:116048 (2021)

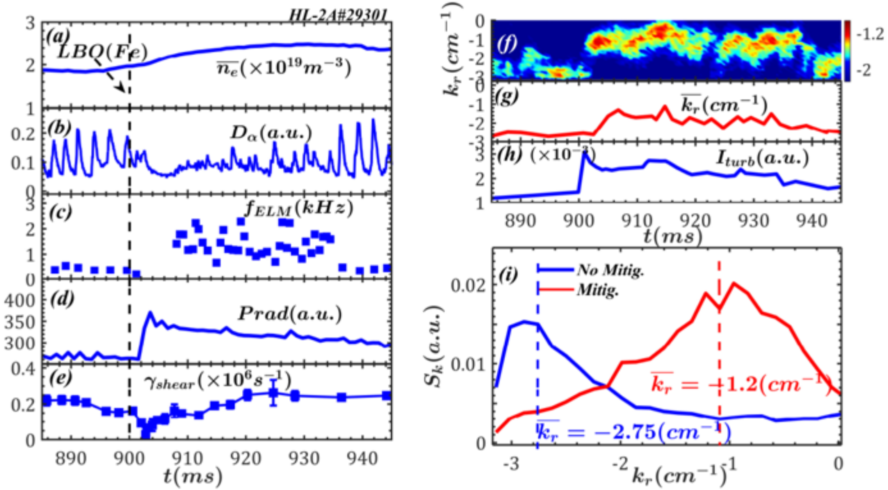






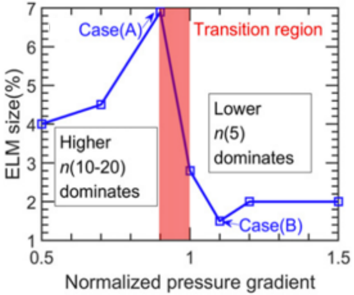
ELM control with impurity seeding

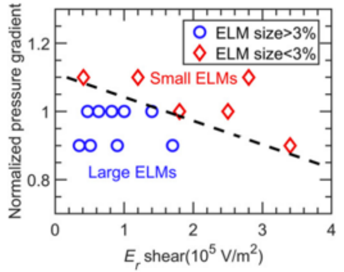
- **Plausible mechanism :**
  - Edge velocity shear decrease
  - Turbulence radial spectral shift
  - Turbulence enhancement
  - ELM mitigation



- **Simulation:**

ELM size can be determined by the changes in pedestal pressure and Er shear due to the impurity seeding





G.L.Xiao et al., Nucl. Fusion 61:116011 (2021)
Y. R. Zhu et al., Nucl. Fusion 62:076011 (2022)

Avalanche Transport Events Triggered by Nonlinear Mode Couplings

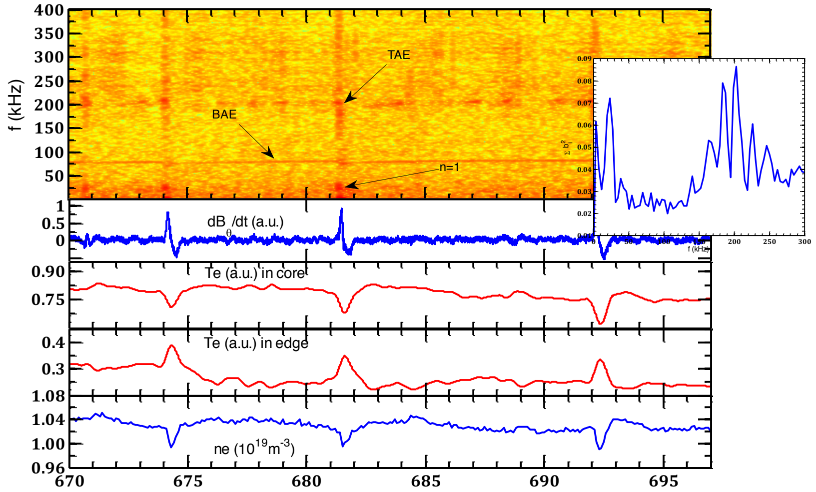
- The nonlinear mode coupling between the core-localized TAEs and m/n = 2/1 fishbone generate multiple modes, cause resonance overlap in real and phase spaces, trigger the avalanche event, enhance electron heat transport

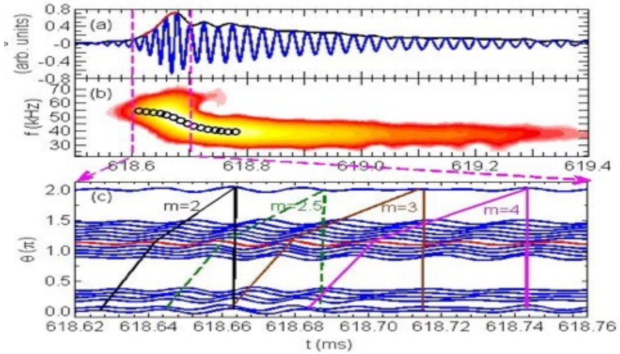
W. Chen, et al., *Nucl. Fusion,* 60 094003 (2020)

- In a strong EPM burst (in another shot), mode radial propagation (m=2→4) causes significant EP transport (EPM convective amplification)

L.M. Yu, et al., *Europhys. Lett.* 138, 54002 (2022)

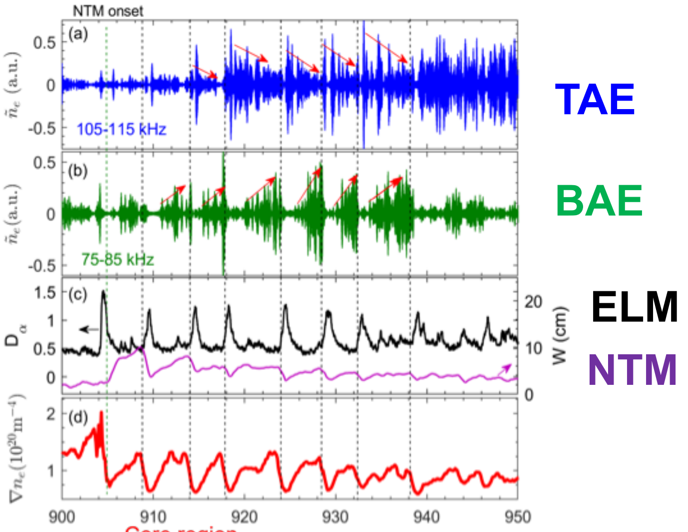
- The non-linear couplings among different scales are crucial for the core-edge integration

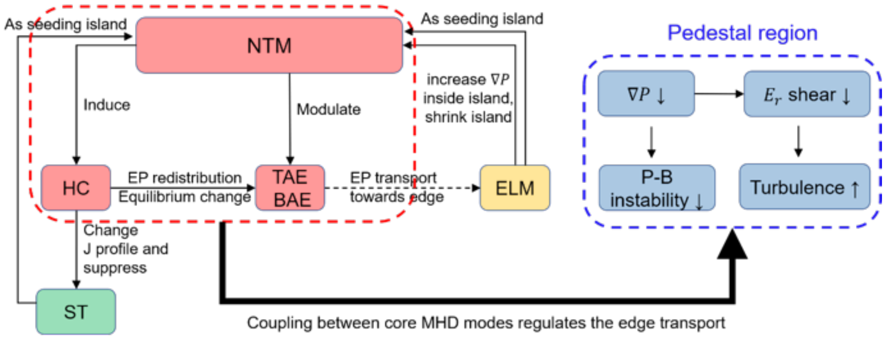




Interaction among core MHD modes and its impact on pedestal transport

- NTM(3/2 or 2/1), TAE(@q ~ 3) /BAE (@q ~ 2) and ELMs co-exist in high β_N H-mode plasmas
- They closely interacted with each other
  - NTM modulate TAE and BAE
  - ELM crash causes a rapid drop of W_{NTM}
  - accompany a saturated 1/1 Helical core (magnetic flux pumping in hybrid?)
  - enhance the fast ion transport
- Such interaction causes increase of pedestal turbulent transport.
- Core-edge interaction!

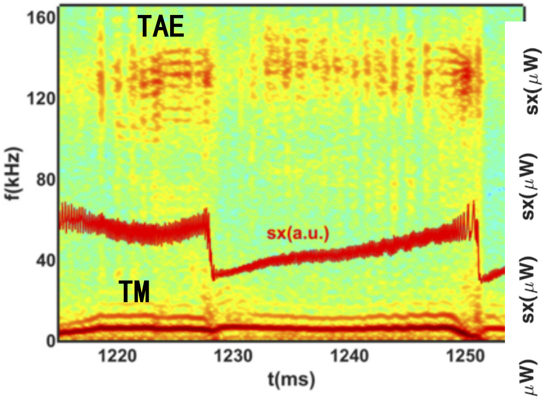


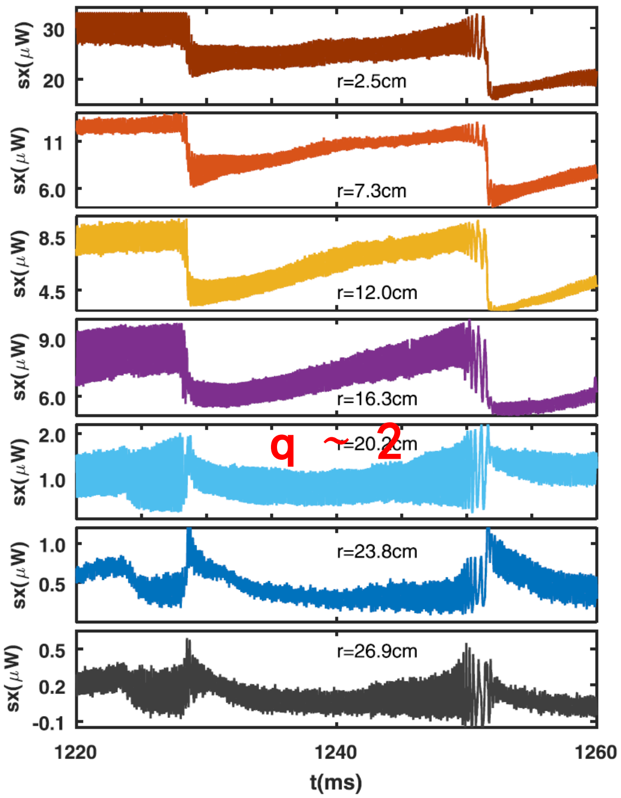


M. Jiang, et al., Nucl. Fusion 62 (2022) 076025

Off-axis sawtooth induced by nonlinear mode coupling

- Off-axis sawtooth @ q ~ 2 induced by nonlinear mode coupling between TAE and tearing mode





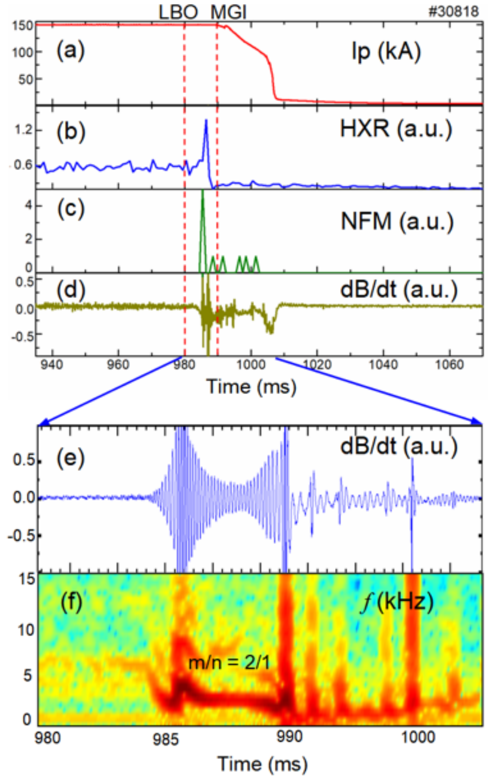
nonlinear coupling enhances fast ion outward transport and leads to loss of toroidal torque,

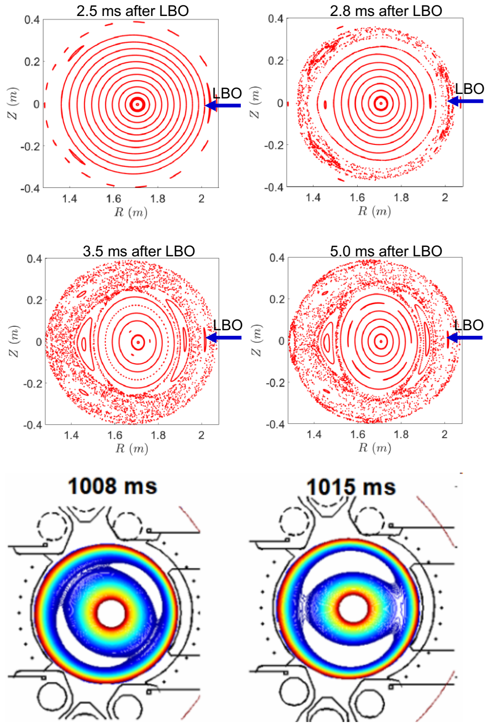
→ results in rotation braking or mode locking，

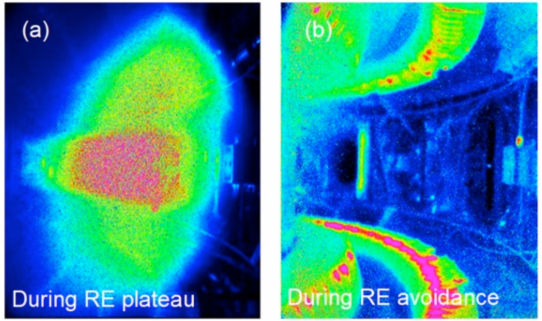
→ saturated tearing mode leads to subsequent collapse

Avoidance of RE generation during disruptions

- **RE generation during disruptions has been successfully avoided for the first time by the LBO-seeded impurity in the HL-2A tokamak.**







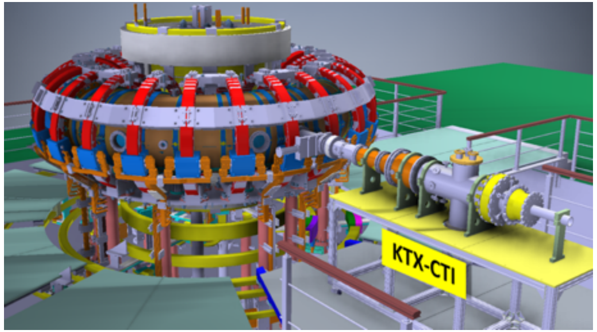
- **A strong m/n=2/1 mode is excited by LBO-seeded impurity.**
- **The magnetic field outside q = 2 is completely randomized, which lead to the fast losses of REs.**

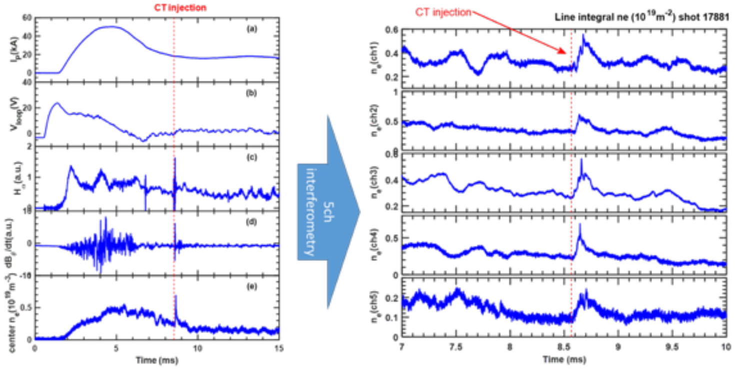
Y.P. Zhang, IAEA FEC (2021)

Fusion Research in Universities

Keda Torus eXperiment in USTC

First compact torus injection experiment

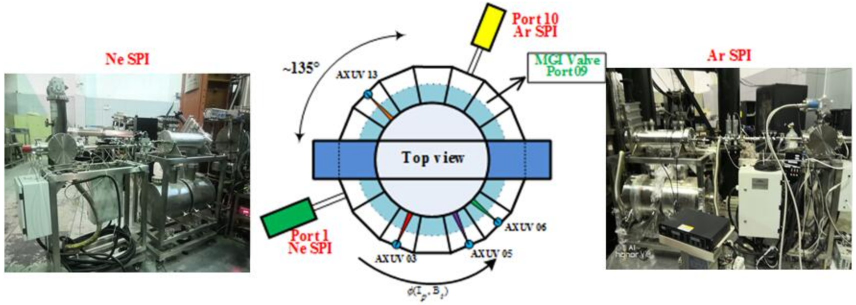


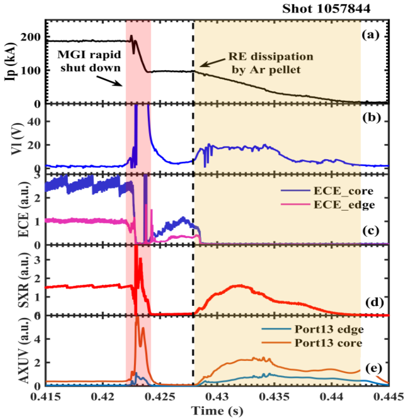


Parameters	Values
Formation bank voltage	20kV
Acceleration bank voltage	20kV
Solenoid bank voltage	3kV, Ψ_{bias} =6mWb
Gas puffing bank voltage	2000V
Outer diameter (D_{ct}) at the exit	8.5cm
Maximum Velocity (V_{ct})	300km/s
Mass (m_{ct})	0.1mg
Number of particles	1×10^{20}
% fueling (of KTX inventory)	5~50%
Length of the injector	3m
Tangential injection angle	25°

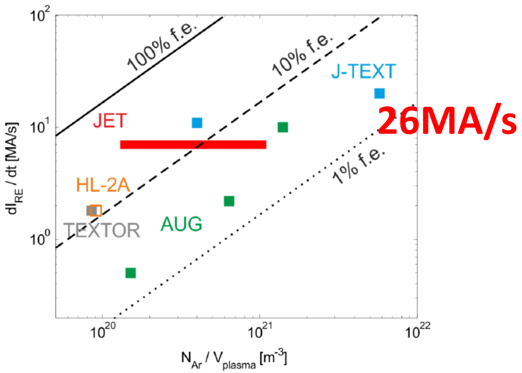
- **KTX Upgrade** allow 1MA operation:
  - ✓ KTX machine are now being upgrade to its full capacity as designed, including Power supply, feedback control and diagnostic systems
  - ✓ Aiming at next step research on 3D physics in MCF plasmas and general physics between Tokamak and RFP configuration
  - ✓ Testing new concepts and technologies of diagnostics

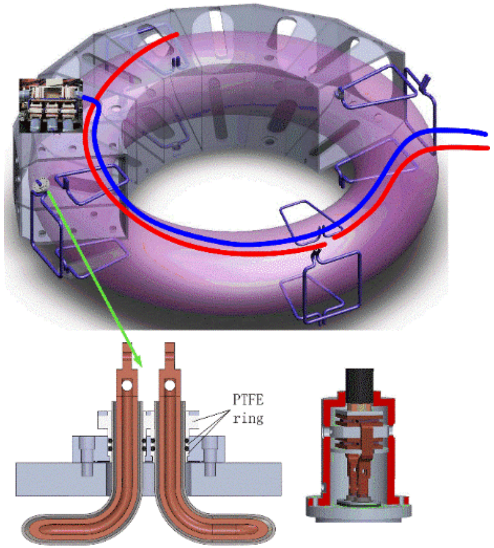
Equipped dual SPI in support of ITPA task force





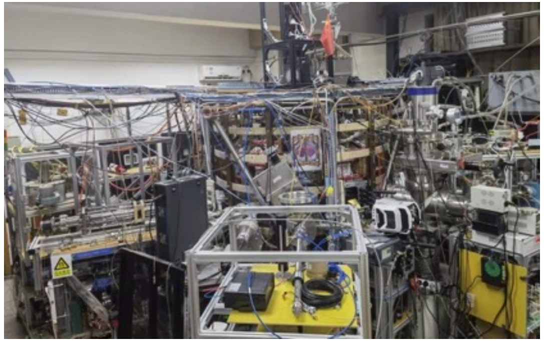
RE current decay rate as function of Ar density

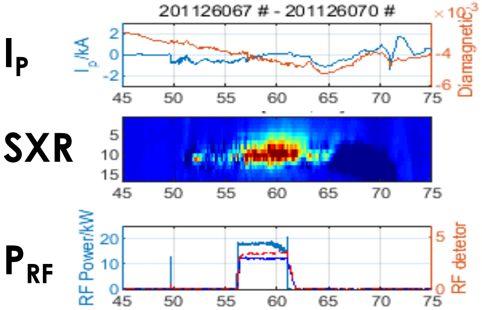




Rotating （6kHz） magnetic perturbation

SUNIST in Tsinghua University



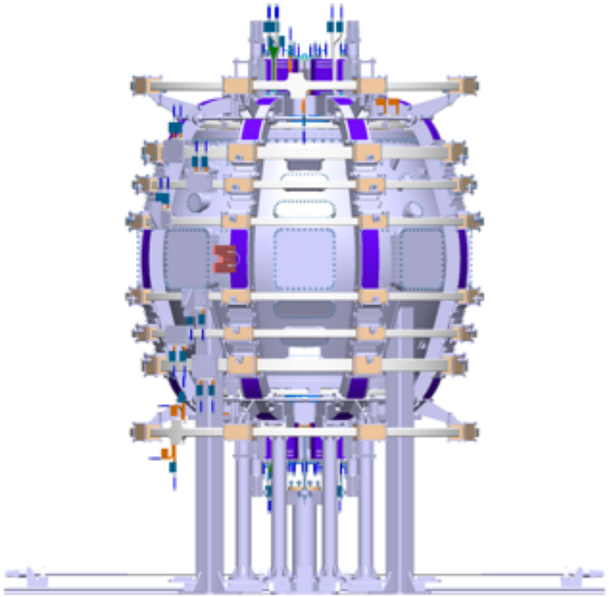


- Successful EBW heating
- density fluctuations of TAEs
- equilibrium reconstruction

A merging experiment in SUNIST-II

Main Parameters:

✓ R/a~0.5m/0.3m; Ip~200-400kA; B_{t0}~0.4-1T; kappa~1.6



Very active research on theory & simulation in universities

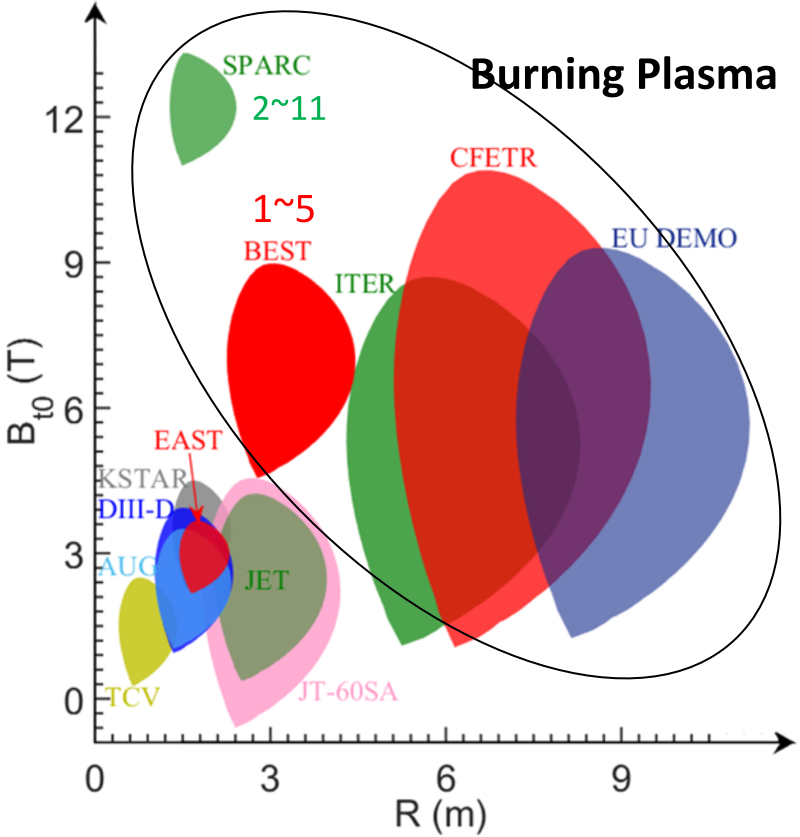
Most projects on energetic particle physics focused in theory/modeling/diagnostics and allocated to Universities in recent 5 years, collaboration with two major facilities are requested

- 氘氚聚变等离子体中alpha粒子过程对等离子体约束性能影响的理论模拟研究 (Transport, IP CAS)
- 面向聚变堆高性能等离子体中快粒子物理实验研究(Experiments, SWIP)
- 氘氚聚变等离子体中磁流体过程的理论和模拟研究(EPM, UZJ)
- 基于非线性回旋动理学的氘氚聚变等离子体约束改善理论和模拟研究(Nl-Gyro-kinetic, USTC)
- 聚变堆等离子体加料、 离子加热模块研发(Fueling and heating, UDL)
- 提升聚变堆等离子体密度参数的关键问题研究(density limit, UZJ)
- 燃烧等离子体中快粒子对芯部约束影响的理论模拟研究(RF-EP, USTC)
- 高分辨热相干散射、安全因子、中子探测诊断技术研究(Diagnostics, USTC)
- 聚变堆燃料粒子合成诊断技术和方法研究(Diagnostics, PKU)
- 聚变堆条件下磁流体稳定性和高能量粒子若干挑战性问题研究 (MHD&EP, Talent)
- 聚变堆条件下约束与输运的若干关键问题研究(T&C, Talent)

Personal perspective on BEST

- **Milestone "Break-Even" under Steady-state**
  - Steady-state scenario exist with sufficient EPs?
  - Hybrid scenario with EPs for long pulse operation
  - EP physics applicable to scenario development
- **At least a proven approach to provide TBR>1**
  - Extrapolatable to DEMO
  - Particle balance issue (fueling, burning, retention, recycling, impurities,…)
- **Constraints on cost and Tritium/neutron budget**
  - Prediction-first
  - Baseline rely on proven physics
  - Exploration from aggressive AT physics

ITER delayed; CFETR difficult in near future




Thank you!